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14. ABSTRACT
In 2004 most scientists working to increase Jc in HTS believed that continuous columnar pinning centers (CCPCs) were ideal. This was based upon elegant ionic radiation studies yielding increased Jc. Our contrary evidence augered for performing an experiment comparing Jc for a wide range of pinning center (PC) continuities and diameters (including CCPCs) produced by high energy ions. (Increased discontinuity correlated with lower diameter.) Multiple-in-line-damage (MILD) PCs had not been systematically studied before this. Results showed an increase in Jc by a factor of 17, for discontinuity near 67%, with PC diameter ~ 6.8 nm and fluence of 10*12/cm*2. Analysis, assuming that the Jc enhancement was caused by the over 10-fold

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Report Title

Improved pinning morphology in HTS with order of magnitude increase in Jc and pinned field.

ABSTRACT

In 2004 most scientists working to increase Jc in HTS believed that continuous columnar pinning centers (CCPCs) were ideal. This was based upon elegant ionic radiation studies yielding increased Jc. Our contrary evidence augered for performing an experiment comparing Jc for a wide range of pinning center (PC) continuities and diameters (including CCPCs) produced by high energy ions. (Increased discontinuity correlated with lower diameter.) Multiple-in-line-damage (MILD) PCs had not been systematically studied before this. Results showed an increase in Jc by a factor of 17, for discontinuity near 67%, with PC diameter ~ 6.8 nm and fluence of 10*12/cm*2. Analysis, assuming that the Jc enhancement was caused by the over 10-fold decrease in MILD PC/ CCPC damage, matched the data well except for a Jc "fishtail" effect, and Jc increase vs. fluence. Analysis of the discontinuities showed they enhanced vortex wandering, and produced entanglement which increased at higher fields, resulting in a fishtail. Wandering vortices jump from gaps in ion tracks to adjacent continuous tracks, diminishing pinning losses. At higher fluence, closer tracks leave less unpinned vortex length. Thus, discontinuities encourage entanglement while restoring pinned vortex length. Both effects increase vortex binding and Jc, while CCPCs suppress entanglement.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. G. Fuchs, K. Nenkov, G. Krabbes, R. Weinstein, A. Gandini, R. Sawh, B. Mayes, and D. Parks, "Strongly enhanced irreversibility field and Bose-glass behavior in bulk YBCO with discontinuous columnar irradiation defects." Invited Journal paper. Supercond. Sci. Technol. 20 (2007) S197-S204.

2. Roy Weinstein, Ravi-Persad Sawh, Alberto Gandini, Bill Mayes and Drew Parks, "Is it really possible to increase Jc by reducing the pining potential?" Invited Journal paper. Supercond. Sci. Technol. 20 (2007) S167-S173.

3. Kent R. Davey, Roy Weinstein, and Ravi Sawh, "Development and Analysis of Trapped Field Magnets in Electromechanical Devices." Proceedings of the 16th International Conference on the Computation of Electromagnetic Fields, in Aachen, Germany, June 24-28 2007; IEEE Transactions on Magnetics; in press.

4. R. Weinstein, A. Gandini, D. Parks, R. Sawh, and B. Mayes "Dependence of Jc on pinning center morphology: An explanation of record Jc observed for very discontinuous columnar pinning of vortices." ISS-2005, Tsukuba, Japan. (Oct. 24-26, 2005); Physica C, 445-448 (2006) 214-218.

5. A. Gandini, R. Weinstein, R. Sawh, D. Parks, and B. Mayes, "Novel experimental result contradicts conventional pinning theory; record-high Jc obtained by reducing the pinning potential." Invited paper, ISS-2005, Tsukuba, Japan. (Oct. 24-26, 2005), Physica C, 445-448 (2006) 317-322.

6. Roy Weinstein, Alberto Gandini, Ravi Sawh, Bill Mayes and Drew Parks, "How and why discontinuous multiple-in-line-damage results in much higher Jc than continuous columnar pinning centers," Invited Paper, PASREG-2005, Tokyo, Japan (Oct. 21-23, 2005); Supercond. Sci. Technol. 19 (2006) S575-S579.

7. I. Kusevic, E. Babic, D. Marinaro, S.X. Dou, R. Weinstein, "Critical currents and vortex pinning in U/n treated Bi2223/Ag tapes," Physica C 408-410 (2004) 524-525.

8. I. Kusevic, E. Babic, D. Marinaro, S.X. Dou, R. Weinstein, "Irreversibility fields and pinning potentials in U/n treated Bi2223/Ag tapes," Physica C 408-410 (2004) 643-644.

9. Roy Weinstein, Alberto Gandini, Ravi-Persad Sawh, Bill Mayes, and Drew Parks, "Experimental test of the postulate that continuous columnar pinning centers produce the highest Jc," Phys. Lett. A, 331 (2004) 276-280.

10. Roy Weinstein, Ravi-Persad Sawh, Alberto Gandini, and Drew Parks, "Improved Pinning by Multiple-In-Line-Damage," Invited talk, PASREG 2003 (Jena, Germany) June 30, July 2, 2003; Supercond. Sci. Technol., 18 (2005) S188-S193.

11. Ravi-Persad Sawh, Roy Weinstein, Drew Parks, and Alberto Gandini, "The Effect of Different Uranium Compounds on the Properties of U-Pt-Y-Ba-O Double Perovskite Pinning Centers in Textured Y-Ba-CU-O Superconductor," PASREG 2003 (Jena, Germany) June 30, July 2, 2003; Supercond. Sci. Technol., 18 (2005) S180-S183.

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(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

1. K. Davey and R. Weinstein, "HTS Trapped Field Magnet Based Motors for Naval Applications", Proceedings of the ASNE Electric Machines and Technology Symposium, Philadelphia PA, May 22-23, 2006.

2. A. Gandini, R. Weinstein, R. Sawh, B. Mayes, D. Parks, "Universal Dependence of the Critical Temperature in HTS on Fractional Volume of Nanosized Disorder. A Study of the Effect of Pinning Centers on Tc." PASREG–2005, Tokyo, Japan (Oct. 21-23, 2005).

3. A. Gandini, R. Weinstein, R.P. Sawh, B. Mayes, D. Parks, "First Experimental Test of the Incorrect Assumption that Continuous Columnar Pinning Centers Produce the Highest Jc in Superconductors," presented at the 2005 Spring Meeting of the Materials Research Society, March 28-April 1, 2005, San Francisco, CA.

4. Alberto Gandini, Roy Weinstein, Drew Parks, Ravi-Persad Sawh, "A Study on the Self-Field Critical Current vs. the In-Field Critical Current in Ag/Bi2223 Tape by Irradiation Technique." PASREG 2003 (Jena, Germany) June 30- July 2, 2003.

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Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

1. Roy Weinstein, Alberto Gandini, Ravi Sawh, Bill Mayes, and Drew Parks, "Higher Jc obtained by reduction of pinning potential," IEEE Transactions on Applied Superconductivity: Proceedings of the 2006 Applied Superconductivity Conference (ASC 2006), Aug 27 – Sept 1, 2006, Seattle, Washington.

2. Alberto Gandini, Roy Weinstein, Ravi-Persad Sawh, Drew Parks, Billy Mayes, "Universal dependence of the critical temperature in HTS on the fractional volume of nanosize defects." IEEE Transactions on Applied Superconductivity: Proceedings of the 2006 Applied Superconductivity Conference (ASC 2006), Aug 27 – Sept 1, 2006, Seattle, Washington.

3. Ravi-Persad Sawh, Roy Weinstein, Drew Parks, Victor Obot, and Alberto Gandini, "Nanometer-sized non-superconducting deposits that fail to act as pinning centers in textured YBCO superconductor." IEEE Transactions on Applied Superconductivity: Proceedings of the 2006 Applied Superconductivity Conference (ASC 2006), Aug 27 – Sept 1, 2006, Seattle, Washington.

4. R. Weinstein et al., "Experimental contradiction of the conventional wisdom that continuous columnar pinning centers result in maximum Jc." EUCAS 05, Vienna (Sept 11-15, 2005). Journal of Physics: Conference Series 43 (2006) 227-230.

5. Alberto Gandini and Roy Weinstein, "Damage effect in HTS irradiated by U fission fragments," Proceedings of the 105th Meeting of the American Ceramics Society, Nashville, TN, (April 27-29, 2003). Invited Talk. Ceramic Transaction, Vol. 149 (2004) pp 135-143.

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 5

(d) Manuscripts

G. Fuchs, K. Nenkov, G. Krabbes, R. Weinstein, A. Gandini, R. Sawh, B. Mayes, and D. Parks, "Bulk YBCO with discontinuous radiation defects: Bose glass behavior and very high Jc. Journal of Physics: Conference Series (2007) in press.

Number of Manuscripts: 1.00

Number of Inventions:

Graduate Students

NAME	PERCENT_SUPPORTED
Goro Osabe	0.50
Jiafu Tang	0.50
FTE Equivalent:	**1.00**
Total Number:	**2**

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Alberto Gandini	1.00
FTE Equivalent:	**1.00**
Total Number:	**1**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Alberto Gandini	1.00	No
FTE Equivalent:	**1.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
Jeffery Diamond	0.25
Lily Ha	0.25
Patricia Nieto	0.25
Lilliana Phamnguyen	0.25
William Rifenburgh	0.25
Adriana Rodriguez	0.25
Jonathan Salazar	0.25
Michael Saldana	0.25
Clinton Seibert	0.25
Harley Skorpenske	0.25
Amanda Skrobarczyk	0.25
Marco Topete	0.25
Binh Trinh	0.25
An Van	0.25
Andrew Windham	0.25
Joseph Yim	0.25
FTE Equivalent:	**4.00**
Total Number:	**16**

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	4.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	4.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	2.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	0.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	1.00

Names of Personnel receiving masters degrees

NAME

Total Number:

Names of personnel receiving PHDs

NAME	
Goro Osabe	
Total Number:	1

Names of other research staff

NAME	PERCENT_SUPPORTED	
Drew Parks	1.00	No
Ravi-Persad Sawh	1.00	No
Harley Skorpenske	1.00	No
FTE Equivalent:	**3.00**	
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Inventions (DD882)

5 **Chemical Pinning Centers for High Temperature Superconductors**

Patent Filed in US? (5d-1) Y

Patent Filed in Foreign Countries? (5d-2) N

Was the assignment forwarded to the contracting officer? (5e) N

Foreign Countries of application (5g-2):

5a: Roy Weinstein

5f-1a: University of Houston

5f-c: I.B.P.D. , room 632 SR1, Univ. of Houston

Houston TX 77204

Foreword

The critical current density, J_c, of a superconductor is generally agreed to be the second most important characteristic, after the critical temperature. In Type II superconductors, localized quanta of magnetic field are formed. If these move freely, dissipative electric fields result, and lower the J_c. The superconductor must contain pinning centers to hold the field quanta in place. Such pinning centers are usually localized regions of non-superconducting material (e.g., damaged HTS) within the superconductor. The absence of the Meissner Effect in these damaged regions results in them acting as attractive potentials for the field quanta and they can pin the field quanta in place.

The creation of pinning centers in high temperature superconductors is particularly difficult because their ideal diameter (at 77 K) is ~ 6.8 nm. By the year 2004 the typical diameters of artificial pinning centers which had been produced was 0.2 – 1 micron by chemical means, and 10 nm by ionic irradiation.

In 2004, the great majority of scientists working in HTS were convinced that gaps in pinning centers, which decrease the pinning potential, would lower J_c. The prevalent attitude was that continuous columnar pinning centers were ideal. Our empirical data indicated otherwise. The work reported here focused on a pinning center geometry previously not systematically investigated. As ion energy becomes very high, the rate of energy delivered to the HTS, dE/dx decreases. Pinning center diameter decreases, and gaps appear in previously continuous columnar damage. We call this region "multiple-in-line-damage" (MILD). We studied a broad range of MILD pinning centers, with diameter of 3.8 – 13.6 nm, and discontinuities of 85% to 0. We found that the reduced pinning center diameters greatly increased J_c and H_{irr}. Analysis of the data, now nearing completion, showed that both the reduced damage and increased entanglement resulting from gaps in MILD pinning centers were responsible for the great increase in J_c. MILD pinning has been shown to be experimentally, and theoretically, superior to CCPC, and the gaps in the pinning centers have been shown to play an important positive role.

List of Illustrations

Statement of the problem studied

In superconductivity, high current density, J_c, is second in importance only to the critical temperature, T_c. Pinning centers (PCs) which hold in place magnetic quanta, are essential to high J_c. The problem studied in this work is: What is the shape and number density of ideal pinning centers?

At the time this research was initiated it had been broadly concluded that ideal PCs were continuous columns of damaged HTS. The great majority of practitioners in this field agreed. See, e.g., [1,2]. In this project we have shown that this assumption is incorrect, and that discontinuities and high number density are essential to optimal pinning.

Results

A narrow range of discontinuities, and damage diameters, resulting from ions with $S_e \sim 2.2$ keV/Angstrom, result in over an order of magnitude increase in J_c.

The leading cause of the conviction of most scientists that CCPCs were ideal was an elegant study by Civali et al [3], using high energy ions. The pinning centers (PCs) used were not in fact CCPCs, and this was recognized by the research group [3]. The pinning centers were nearly 40% discontinuous, as shown by TEM studies of the ionic damage, made by the authors. However, Civali et al analyzed the data *as if* the pinning centers were CCPCs. It is not unusual in physics research for authors to analyze data, using an assumption for which theory already exists, or an assumption making for a simpler theoretical analyses. The pinning centers used by the researchers increased J_c dramatically, to the highest values then seen in crystalline HTS.

The study was such a success that almost everyone set aside the fact that the pinning centers used were discontinuous, and concluded that CCPCs result in highest J_c. It was generally assumed that the "small" discontinuities involved would not significantly effect results and that the PCs were essentially continuous.

Our research group had been working with ion bombardment to produce bulk magnets composed of HTS. We observed that very high J_c resulted from very discontinuous pinning centers. These were in the form of badly broken columns, and even a string of beads, which had discontinuities of up to 80% [4, 5, 6,7].

Various world groups studying ion damage as a problem in nuclear physics had made quantitative progress in gathering empirical knowledge concerning the diameter of ionic pinning centers [8,9]. Civale et al [3] relied upon such studies as motivation for their work. The Sn ions they used had damage tracks ~ 10 nm in diameter and, as noted above, 40% discontinuity.

Civale et al [3] had commented that J_c continued to increase as the ion fluence (which is equivalent to the number of pinning centers/cm^2) was increased. The first empirical hint our group had that something was wrong with the conclusion that CCPCs were optimum, was a theoretical calculation showing that the diameter of the damage in Civale's work was so large that any further increase in fluence, beyond the maximum fluence reported by the group, would *decrease* the J_c, because of the extensive damage. We also showed experimentally that J_c did indeed decrease at fluences just above the maximum fluence they used.

Our research group then theoretically studied the decrease of J_c due to the effect of the damage inherent in pinning centers, including effects of loss of superconducting volume, decrease in T_c, and blocking of percolation paths. We published a paper [10] which concluded, on the basis of empirical inconsistencies, that smaller diameters than could be obtained for CCPC were essential to increase J_c using ionic damage, and that an order of magnitude increase in J_c was available at some as-yet-unknown smaller diameter and increased discontinuity.

The great majority of our co-workers in HTS assumed we were talking nonsense. An increase in discontinuity would decrease pinning potential and, they reasoned, J_c.

We then concluded that it would require a clear experimental demonstration of higher J_c obtained with pinning centers of smaller diameter and greater discontinuity, to prove our conclusion. We designed an experiment in which J_c was to be measured vs. diameter and discontinuity, and in which discontinuity varied from 85% to 0, and the diameter varied from 3.8 nm to 13.6 nm. During the period of experimental design we continued to try to convince colleagues that our proposal merited consideration [12].

We applied to ARO for funding to continue this work, and proceeded to perform the experiment using the ~60 GeV uranium beam available at the GSI accelerator, Darmstadt, Germany.

<u>Our aim was to unambiguously determine whether the highest J_c was produced by CCPC, or by MILD pinning centers. If an optimum pinning center existed, as disclosed by a peak in J_c we aimed to locate that peak to 10%.</u>

Summary of the most important results

Early results of the experiment are shown in Fig. 1, which graphs the increase in J_c vs. "S_e." S_e is the rate at which the ion delivers energy, and is equal to dE/dx used by the nuclear community. It had been shown by others that radius of damage [8] and discontinuity [9] both were functions of S_e. The diameter of the ionic damage is linearly proportional to S_e. It varies from 3.8 nm to 13.6 nm, for the range of S_e in Fig. 1. The discontinuity fraction varies as the 1.5 power of S_e. It varies from 0.85 to 0 for the range of S_e in Fig. 1.

The results were very startling. J_c exhibited a clear peak. At best, the peak was 17 times higher than the initial J_c. Bulk YBCO was used in the experiment, and J_c set a new world's record of 321 kA/cc for this variety of HTS, over 5 times the earlier record.

Both PC diameter and gaps were varied (via S_e), and the best results at 77 K were for (a) a discontinuity of 66%, (b) a fluence five times higher than that limiting Civale et al [3], and (c) pinning center diameter of 6.8 nm. (We note the reassuring fact that 6.8 nm is the predicted optimum pinning diameter, from basic pinning theory.)

The value of J_c with 66% discontinuity was higher than that with 0% discontinuity (i.e., CCPCs) by a factor of almost 6.

We reported these results in a journal article [13], and at meetings [14, 15]. During this period we continued analysis. Our initial assumption was that the reduced damage of MILD pinning, e.g., vs CCPC, was the sole cause of the dramatic increase in J_c. We reported this analysis, as well as the data, in four papers at two conferences [16, 17,18]. The analysis, based upon the effects of damage on percolation, and on change in T_c, led to a prediction of peak J_c at a value of S_e in agreement with the experimental observation.

However, some unexpected results were observed in this analysis (e.g., the value of S_e for the peak in J_c changes slightly with fluence; e.g., a "fishtail" behavior in J_c vs. applied field, B_A, is observed.)

We added to the analysis the effect of vortex motion in the regions of gaps in the pinning centers. This additional vortex freedom was shown to result in vortex wandering, and consequent vortex entanglement (with other vortices) which increased with field [19]. Entanglement has long been known to increase vortex stability and J_c, and acts as a second source of pinning potential (the first is any non-superconducting region within a superconductor). When vortices entangle, movement of a single vortex (of field B) requires that it crosses another vortex of field B. This doubles the magnetic field, but quadruples the energy, and thus provides a potential barrier leading to additional pinning. As applied field increases, the number of vortices/cm^2 increases. This enables a vortex to entangle with several vortices, thus increasing total pinning and consequently increasing J_c. Hence J_c increases with applied B, contrary to its usual behavior. This is seen in Fig. 2. Fig. 3 shows the result of detailed analyses of the position of the peak in the J_c "fishtail", B_{max}, which showed convincingly that the physical interpretation given above is accurate.

CCPCs act to suppress entanglement. At all points in a continuous pinning center the vortex is trapped (except for extreme thermal fluctuations). In MILD pinning centers the vortex is given repeated intervals of freedom, and can use these for entanglement. This is one source of increased J_c for MILD pinning centers.

The above process also explains why J_c increases for higher fluence. At lower fluence, the ionic pinning centers are further apart. When a vortex wanders off the ionic trail of damage at a gap (i.e., when it is not pinned) it will normally take the shortest distance to the next pinning center in order to minimize energy. In this action of "jumping" from one ionic pinning center to another, the vortex is not pinned for some distance. That distance shrinks as the fluence increases and the ionic pinning centers move closer together. Therefore, as fluence increases, the unpinned "jumping" distance decreases, the *average* pinning energy decreases, and peak J_c increases.

Other checks have been done to be sure our GSI data is not an artifact. The J_c agrees with, e.g., Civale's [3] J_c where S_e and fluence are equal to Civale's. The J_c agrees with our earlier values of J_c from fission, when the differences in entanglement are included.

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[15] R. Weinstein et al., "Experimental contradiction of the conventional wisdom that continuous columnar pinning centers result in maximum J_c." (EUCAS 05), Vienna (Sept 11-15, 2005). Journal of Physics: Conference Series 43 (2006) 227-230.

[16] Roy Weinstein, Alberto Gandini, Ravi Sawh, Bill Mayes and Drew Parks, "How and why discontinuous multiple-in-line-damage results in much higher J_c than continuous columnar pinning centers," Invited Paper, PASREG-2005, Tokyo, Japan (Oct. 21-23, 2005); Supercond. Sci. Technol. 19 (2006) S575-S579.

[17] A. Gandini, R. Weinstein, R. Sawh, B. Mayes, D. Parks, invited paper, "Universal Dependence of the Critical Temperature in HTS on Fractional Volume of Nanosized Disorder. A Study of the Effect of Pinning Centers on T_c." PASREG–2005, Tokyo, Japan (Oct. 21-23, 2005).

[18] R. Weinstein, A. Gandini, D. Parks, R. Sawh, and B. Mayes "Dependence of J_c on pinning center morphology: An explanation of record J_c observed for very discontinuous columnar pinning of vortices." ISS-2005, Tsukuba, Japan. (Oct. 24-26, 2005); Physica C, 445-448 (2006) 214-218.

[19] Roy Weinstein, Ravi-Persad Sawh, Alberto Gandini, Bill Mayes and Drew Parks, Invited Journal paper, "Is it really possible to increase J_c by reducing the pining potential?" Supercond. Sci. Technol. 20 (2007) S167-S173.

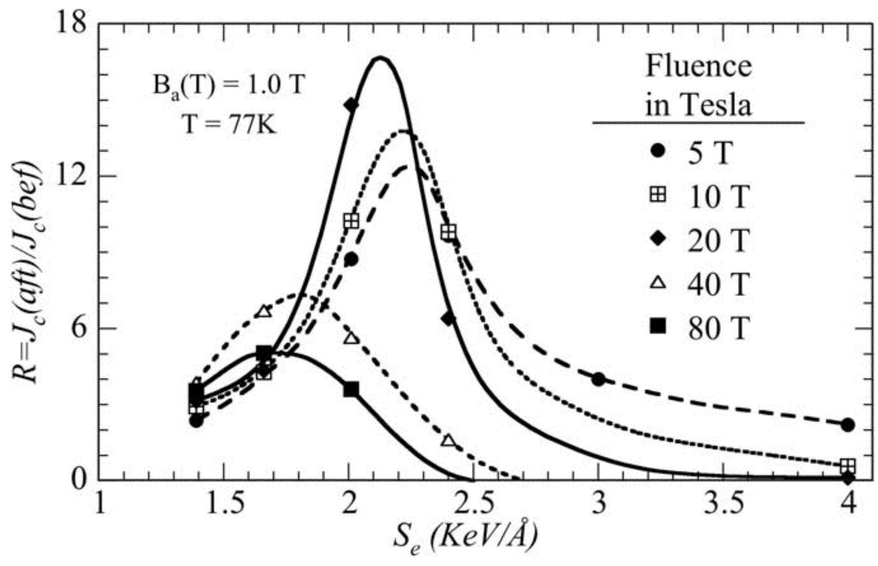

Fig. 1. Early results of the GSI experiment showing peaks in J_c at values of S_e resulting in very discontinuous pinning centers (e.g., 67% discontinuity at $S_e \sim 2.1$ keV/Angstrom), and increases in J_c by as much as a factor of 17.

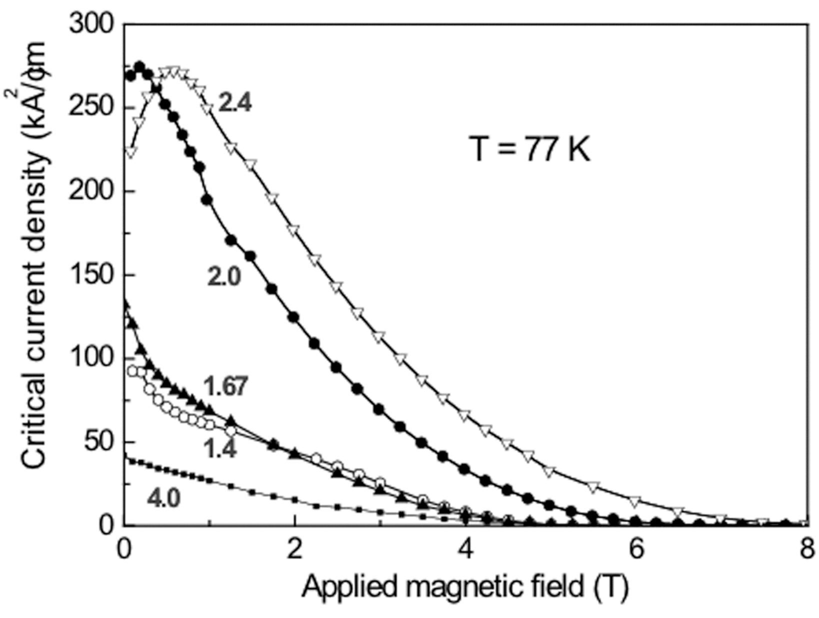

Fig. 2. Data showing J_c vs. applied field, B_A. Note that at high values of J_c, J_c initially increases as field increases (called the fishtail effect) contrary to usual behavior.

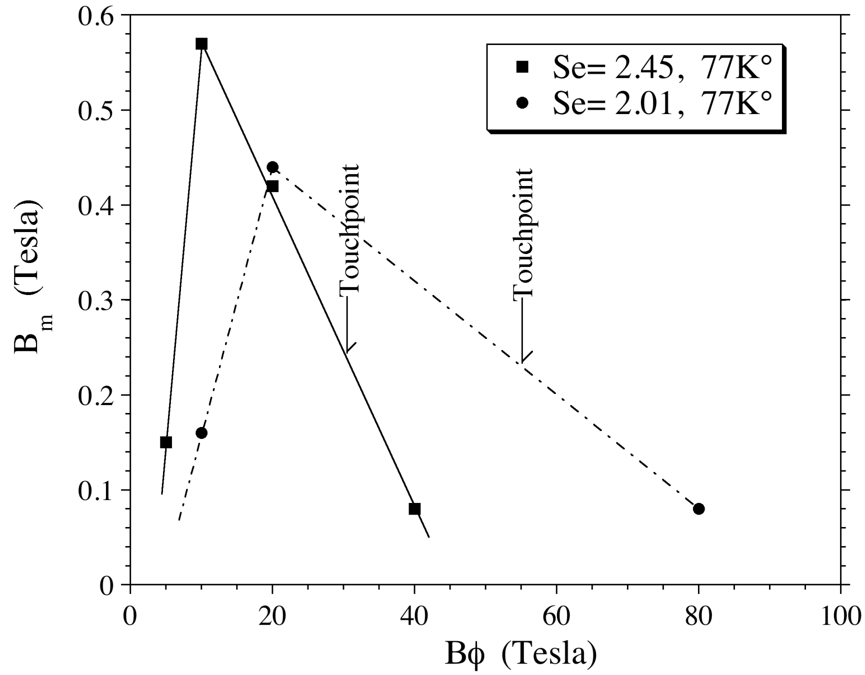

Fig. 3. Analysis of fishtail effect, showing the increase in B_{max} of the fishtail vs. fluence. The fact that B_{max} is linear with fluence strongly points to the fishtail source being PC gaps. The effect ceases when PCs touch due to very high fluence.